Proton Decay in Orbifold GUTs

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Intensity Frontier
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Outline

Evolution of SUSY GUTs

- 4 dimensional SUSY GUTs
- 5 dimensional orbifold GUTs
- String orbifolds $\Longleftrightarrow$ orbifold GUTs
- Conclusions

Supersymmetric Grand Unified Theories

- $M_Z \ll M_G$ "natural"
- Explains charge quantization & Families
- Unification of gauge couplings
- Yukawa coupling unification
- + family symmetry ➡ fermion mass hierarchy
- Neutrino masses via See-Saw
- LSP - dark matter candidate
- Baryogenesis via leptogenesis
- SUSY desert ➡ LHC probes physics at M_{Pl}
- SUSY GUTs "natural extension of SM"

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- 4 dimensional SUSY GUTs
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Grand Unification - SO(10) GUT

	State	Y $= \frac{2}{3}\Sigma(C) - \Sigma(W)$	Color C spins	Weak W spins
1	$\bar{\nu}$	0	− − −	− −
10	$\bar{e}$	2	− − −	+ +
	u_r	$\frac{1}{3}$	+ − −	− +
	d_r		+ − −	+ −
	u_b		− + −	− +
	d_b		− + −	+ −
	u_y		− − +	− +
	d_y		− − +	+ −
	$\bar{u}_r$	$-\frac{4}{3}$	− + +	− −
	$\bar{u}_b$		+ − +	− −
	$\bar{u}_y$		+ + −	− −
$\bar{5}$	$\bar{d}_r$	$\frac{2}{3}$	− + +	+ +
	$\bar{d}_b$		+ − +	+ +
	$\bar{d}_y$		+ + −	+ +
	ν	−1	+ + +	− +
	e		+ + +	+ −

Georgi
Fritzsch & Minkowski

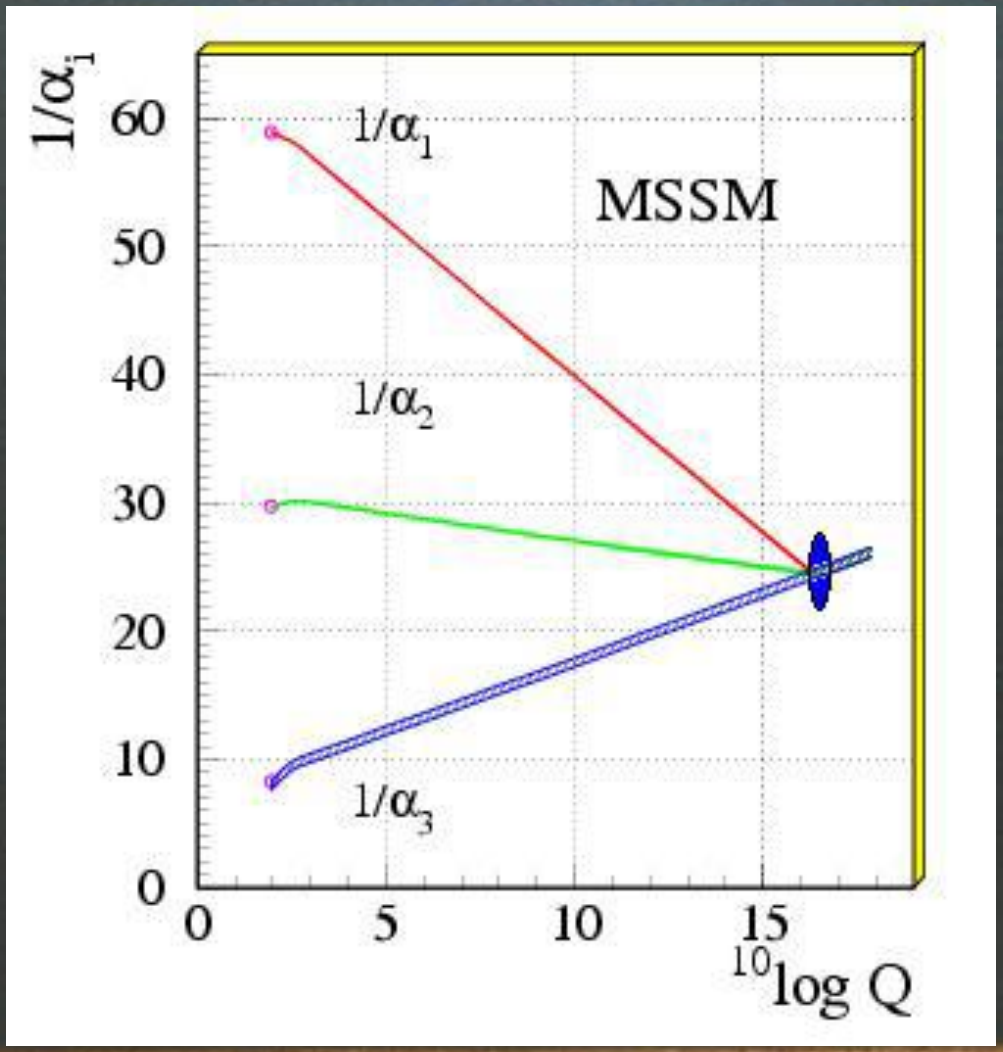
spinor repsn.
of SO(10)

tensor product
of 5 spin ½
w/even no. + signs

Georgi & Glashow

SU(5)

Gauge coupling unification

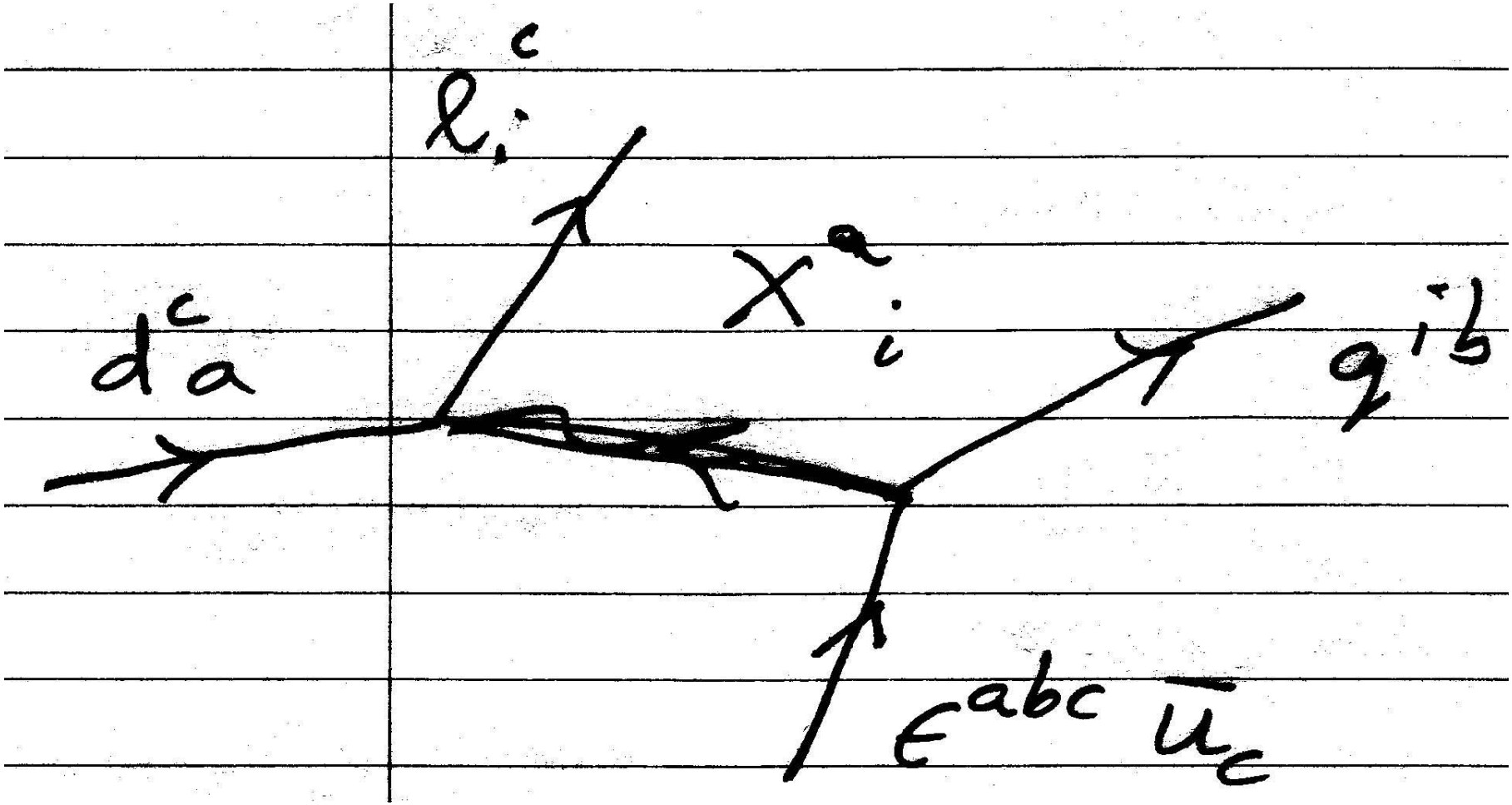


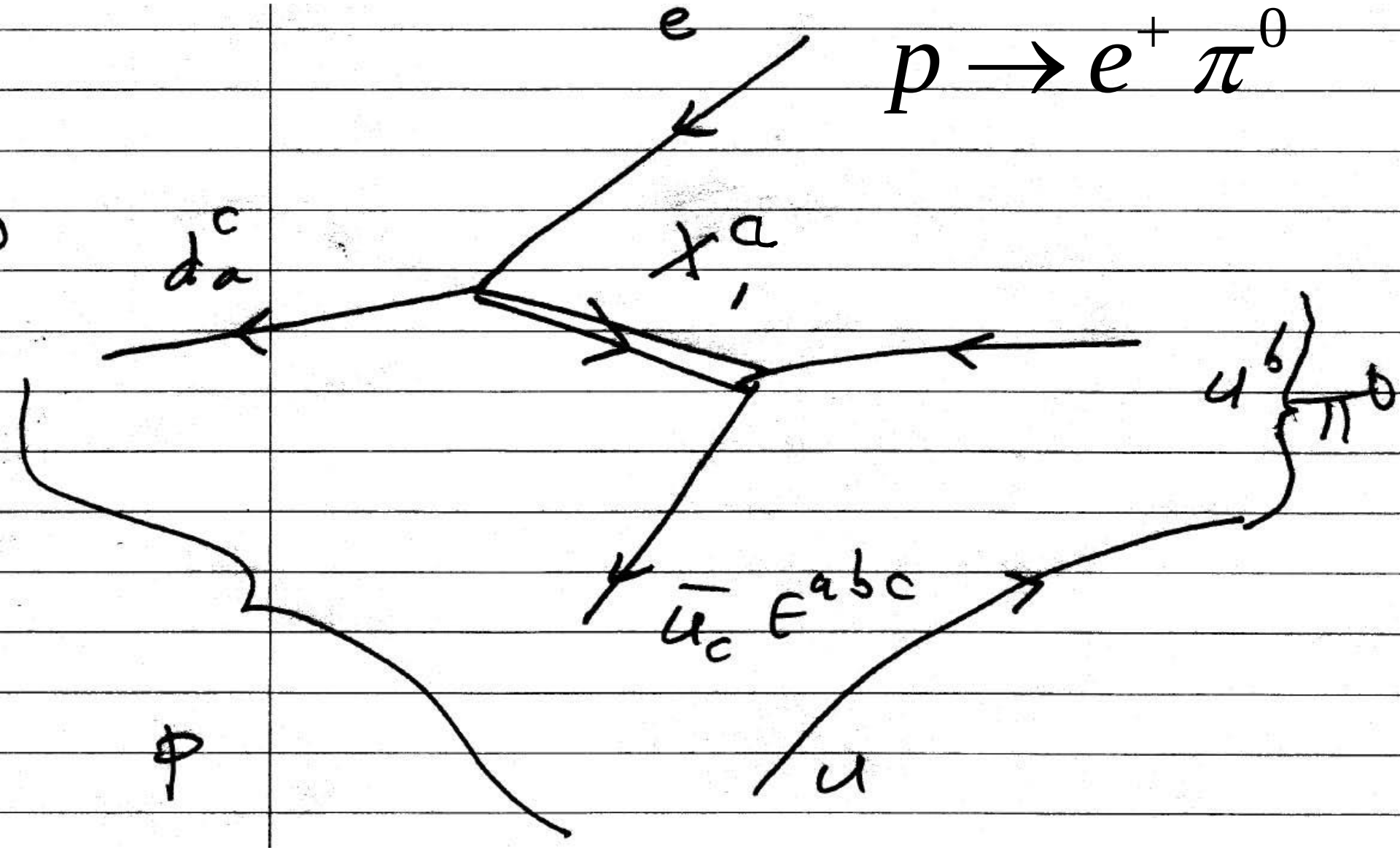
Dimopoulos, Raby & Wilczek
PRD24, 1681 (1981)

LEP data !!

Amaldi, de Boer & Furstenau,
PLB260, 447 (1991)

Proton decay - dim 6 operators




$p \to e^+ \pi^0$
e
d_a^c
X_1^a
u
π^0
$\bar{u}_c \epsilon^{abc}$
p
u

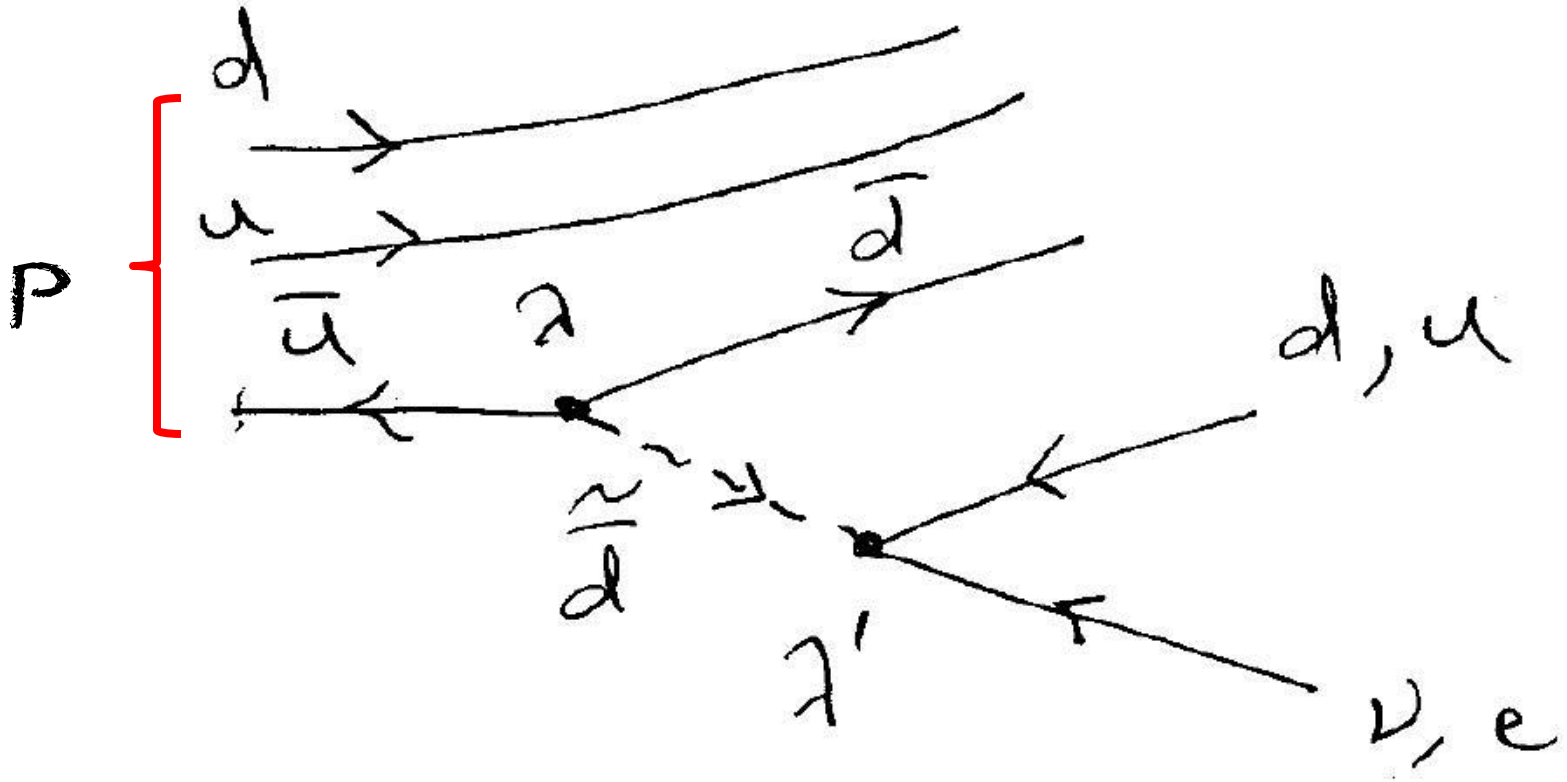
$$\tau_p \Big/ Br(p \to e^+ \pi^0) \geq 1 \times 10^{34}\ yrs \qquad Super - Kamiokande$$

$$\sim \frac{M_G^4}{g_G^4\, m_p^5}$$

$$\approx 10^{36 \pm 2}\ yrs \qquad Theory$$

Proton decay - dim 4 operators

$$10\,\bar{5}\,\bar{5} \supset \lambda\; U^c D^c D^c + \lambda'\; \mathrm{Q\,L}\, D^c \; + \lambda''\, E^c\, \mathrm{L\,L}$$



$$p \to \pi^+ \;\; \bar{\nu} \;\; \text{or} \;\; \pi^0 \;\; e^+$$

$$\Gamma_p \approx \frac{(\lambda\ \lambda')^2\, m_p^5}{m^4}$$

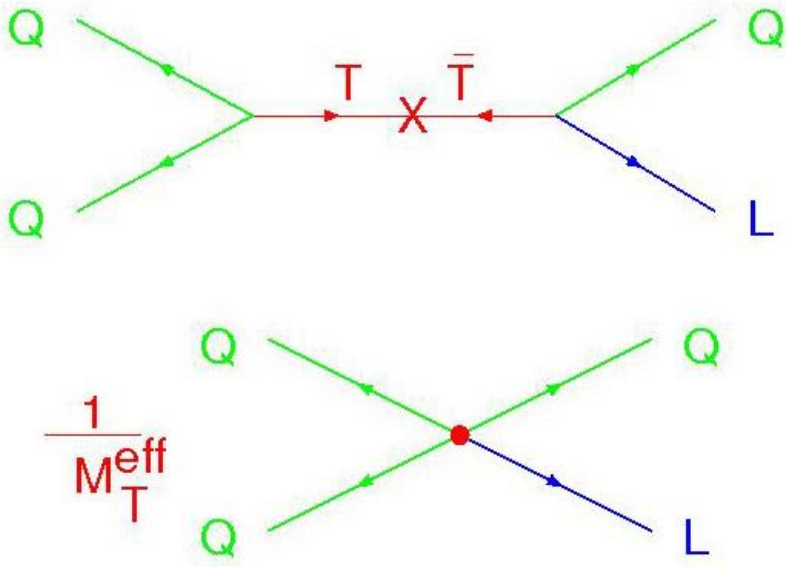
$$\frac{\lambda\lambda'}{m^2} < \frac{g_G^2}{M_G^2} \leq 10^{-32}\, GeV^{-2} \quad \Rightarrow \quad \lambda\lambda' < 10^{-26} \left(\frac{m}{1TeV} \right)^2$$

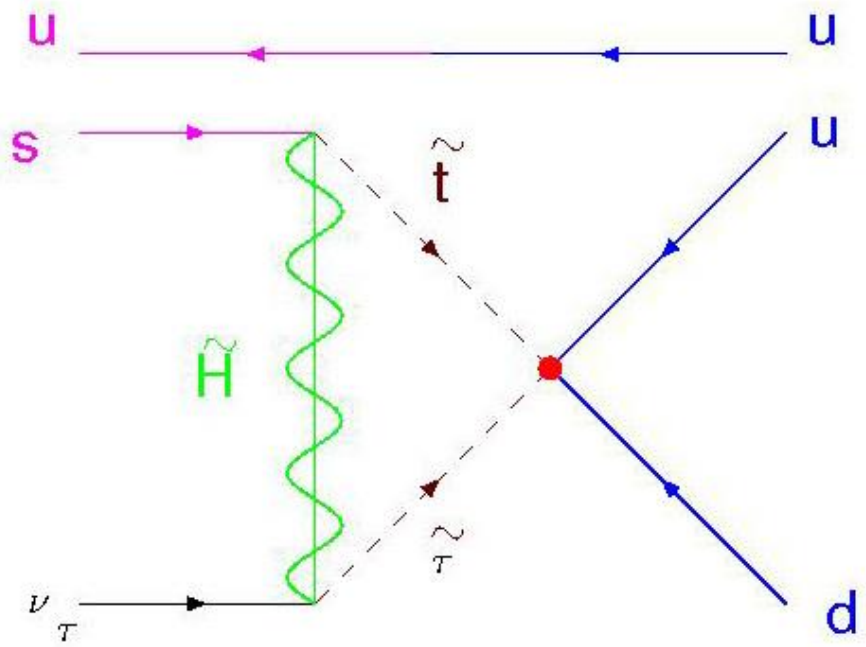
$\mathbb{Z}_2$ matter parity excludes dim 4 operators

F $\rightarrow$ -F, H $\rightarrow$ H

Proton decay - dim 5 operators

$$10\,1010\,\bar{5} \supset \mathrm{Q\,Q\,Q\,L} + U^c\,U^c\,D^c\,E^c$$





$$(LF) \propto \frac{\lambda_t \, \lambda_\tau}{16\pi^2} \frac{\sqrt{\mu^2 + M_{1/2}^2}}{m_{16}^2}$$

$$A(p \to K^+ \bar{\nu}) \propto \frac{c \, c}{M_T^{eff}} (\mathrm{LF})$$

c ~ Yukawa couplings

minimize (LF) $\Rightarrow$ $\mu, M_{1/2} \ll m_{16}$

maximize M_T^{eff} $\Rightarrow$ $M_T^{eff} >> M_{Pl}$

$T, \bar{T}$ anything with Q #s of $D, \bar{D}$

coupling to quarks and leptons

Dim 5 B ξ L violating operators

$$\kappa^{(1)}_{ijk\ell} Q_i Q_j Q_k L_\ell + \kappa^{(2)}_{ijk\ell} \bar{U}_i \bar{U}_j \bar{D}_k \bar{E}_\ell$$

$$\tau\left(p \to K^+ \bar{\nu} \right) > \ 2.3 \times 10^{33} \text{ years}$$

$$\sim \ (1/3 - 3) \times 10^{34} \text{ years} \quad \textit{Theory}$$

$$\kappa^{(1,2)} \left[= \frac{c\ c}{M_T^{eff}} \right] \equiv \frac{1}{\Lambda} \ \leq \ 10^{-27} \text{ GeV}^{-1}$$

Most complete 4D SUSY GUTs

"From minimal to realistic supersymmetric SU(5) grand unification"

Altarelli, Feruglio & Masina

JHEP 0011(2000)040

"Constraining Proton Lifetime in SO(10) with Stabilized Doublet-Triplet Splitting"

Babu, Pati & TavartKiladze

JHEP 1006 (2010) 084

Problems of SUSY GUTs

- GUT symmetry breaking
- Higgs doublet-triplet splitting

Missing partner mechanism SU(5)

$$W \supset 75^3 + M\ 75^2 + \mathrm{H}_u\ 75\ H_{50} + \overline{H}_d\ 75\ H_{\overline{50}} + X\ H_{\overline{50}}\ H_{50}$$

Missing VEV mechanism SO(10)

$$W \supset 45^4 + M\ 45^2 + \mathrm{X}\left(\overline{16}\ 16\right)^2 + F(X)$$

$$+\overline{16}'\left(S\,45 + S_1\right)\ 16 + \overline{16}'\left(S\,45 + S_2\right)\ 16' + 10\,45\,10' + X'\left(10'\right)^2$$

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Orbifold GUTs in 5 or 6 dimensions

GUT symmetry breaking

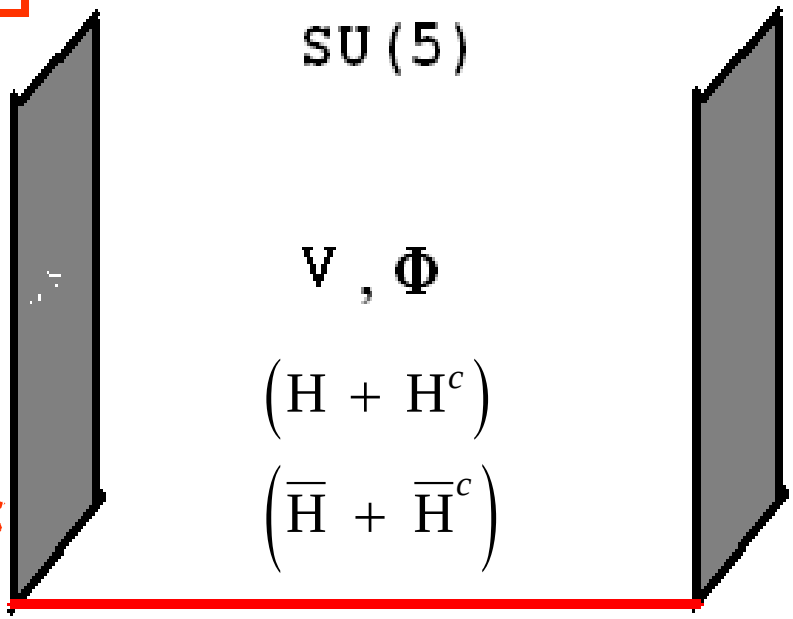
Doublet-Triplet splitting

Kawamura; Hall & Nomura; Contino, Pilo, Rattazzi & Trincherini; Altarelli, Feruglio & Masina; Dermisek & Mafi; H.D. Kim & Raby; Asaka, Buchmuller & Covi; Lee; Hebecker & March-Russell; H.D.Kim, Raby & Schradin

Hall & Nomura SU(5) GUT on M x $S^1/(Z_2 \times Z'_2)$

GUT symmetry breaking
Higgs D-T splitting
via orbifold BCs

b-τ Yukawa unification



$10 + \bar{5}$

3^{rd} family

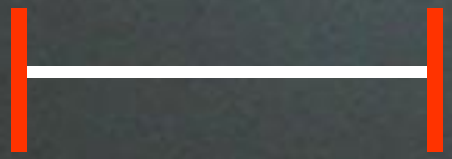
Brane states

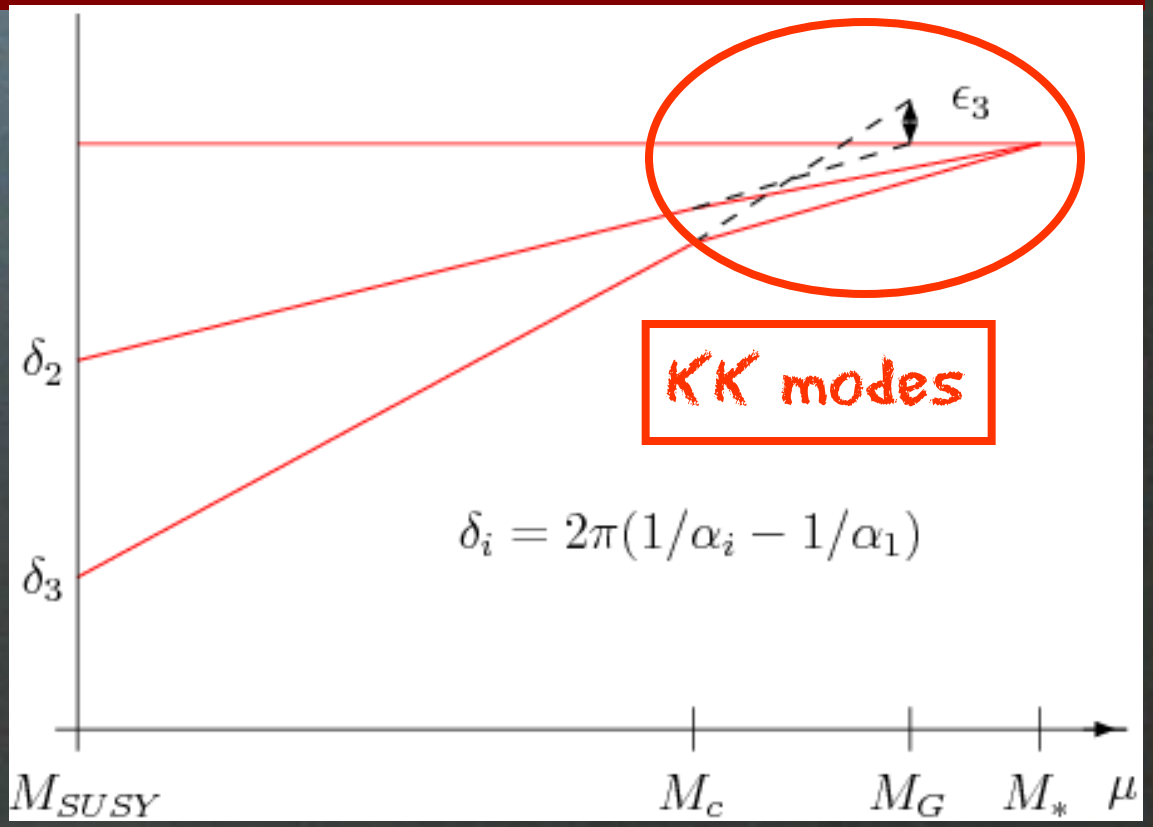
1st & 2nd families in bulk

Suppress proton decay

G.C. Unif. & Proton decay > 4D

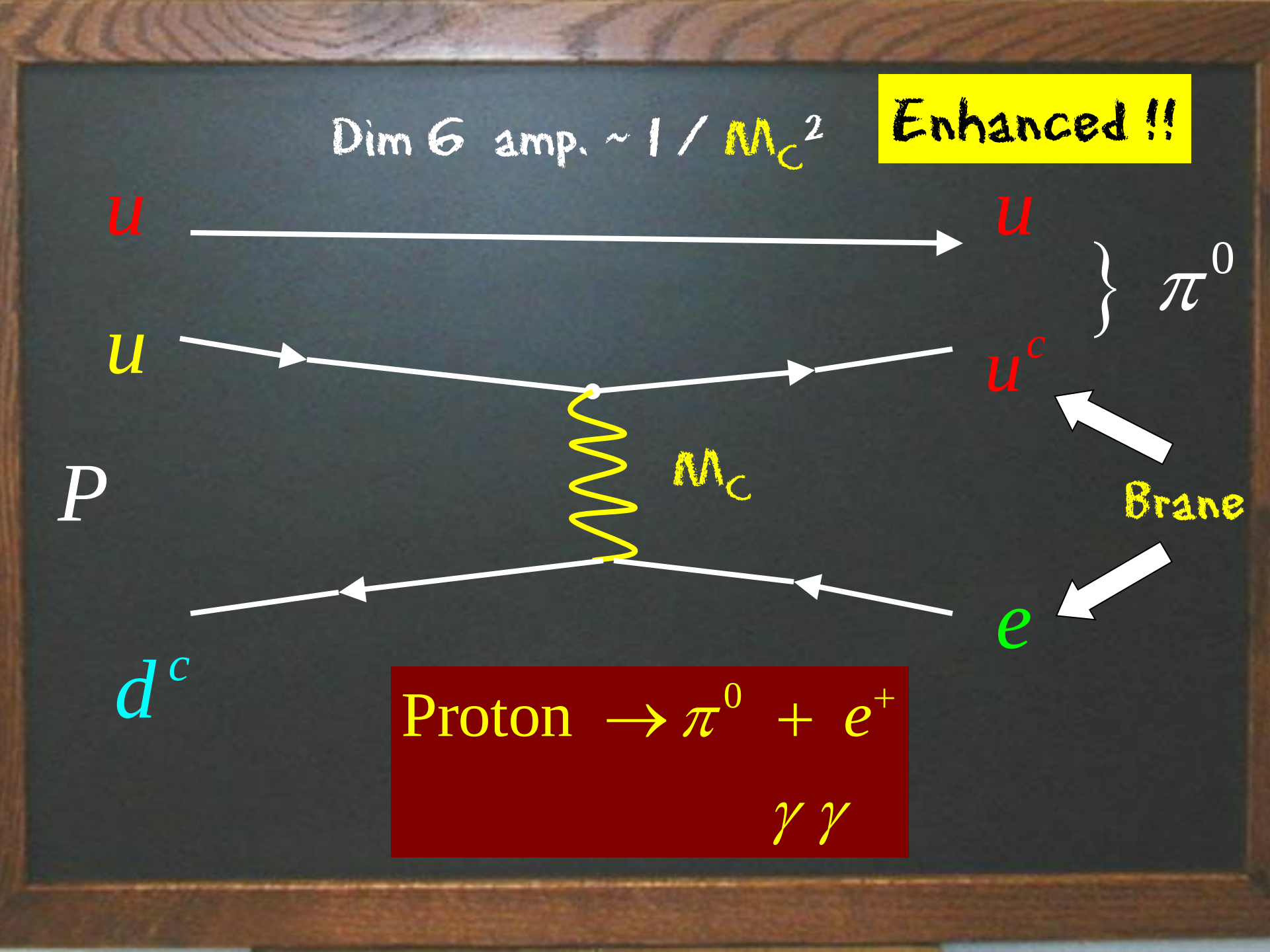
5D Orbifold GUT





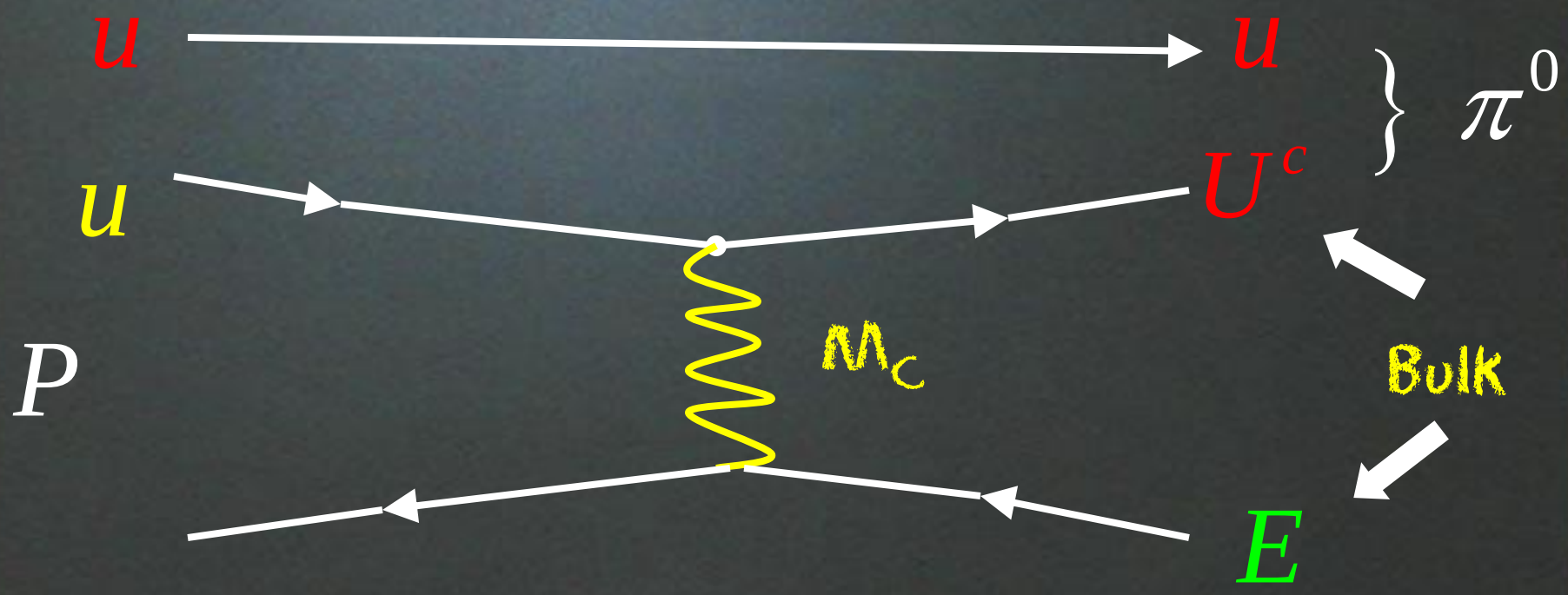
$M_c \sim 1/\pi R < M_G < M_*$

Dienes et al., Hall & Nomura, Kim & S.R., Feruglio et al.


Dim 6 amp. ~ 1 / M_C^2
Enhanced !!
u
u
u
π^0
u^c
P
M_C
Brane
e
d^c
Proton $\rightarrow \pi^0 + e^+$
$\gamma\ \gamma$

Dim 6 amp. ~ $1 / M_C^2$

Suppressed !!



Proton $\rightarrow \pi^0 + e^+$

$\gamma\,\gamma$

Orbifold GUTs in 5 or 6 dimensions :

- GUT breaking via Orbifold "Parity"
- Higgs doublet - triplet splitting via Orbifold "P"
- NO proton decay via Dim 5 operators
  due to R symmetry (model dependent)
- Proton decay via Dim 6 operators can be suppressed, BUT typically enhanced
  (model dependent)
- Matter localization determines Yukawas

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UV completion

Orbifold GUTs in 5 or 6 dimensions
Derived from heterotic string in 10 D

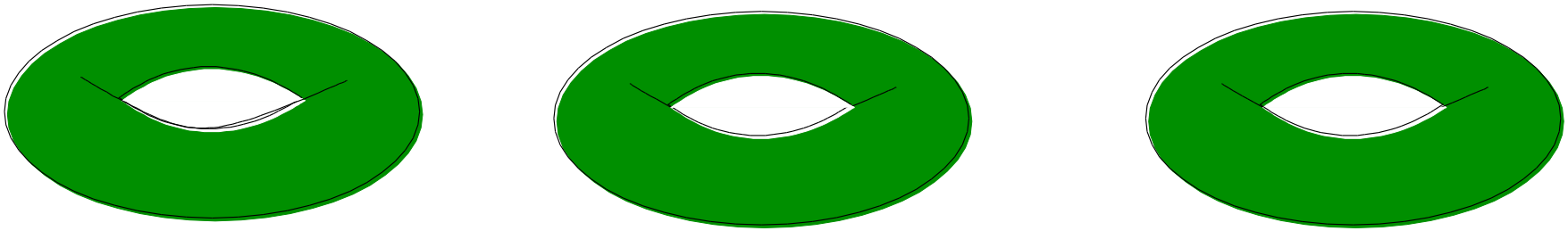
Kobayashi, Raby & Zhang; Forste, Nilles, Vaudrevange & Wingerter; Buchmuller, Hamaguchi, Lebedev & Ratz; JE Kim, JH Kim & Kyae; Buchmuller, Ludeling & Schmidt; Lebedev, Nilles, Raby, Ramos-Sanchez, Ratz, Vaudrevange & Wingerter

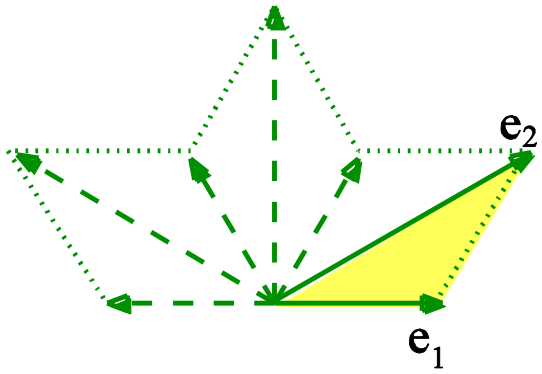
Road to the MSSM with R-parity
Lebedev et al. - 0708.2691(hep-th)

Find 15 models from orbifold compactification of E(8)xE(8) heterotic string

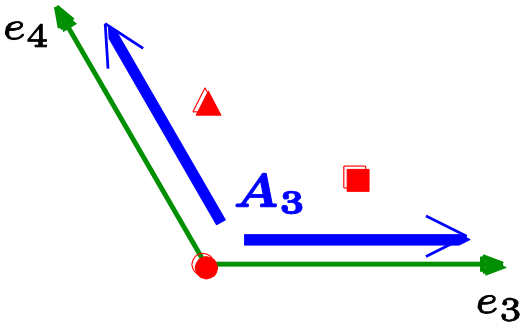
- ✓ MSSM spectrum at low energy
- ✓ Exact R parity
- ✓ Light Higgs
- ✓ Non-trivial charged fermion masses
- ✓ Neutrino masses via See-Saw

Compactify $E(8)\times E(8)$ heterotic string on $(T^2)^3/(Z_3 \times Z_2)$ + Wilson lines (A_2, A_3)

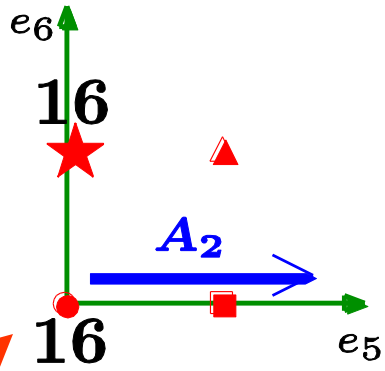




G_2 root lattice



SU(3) root lattice

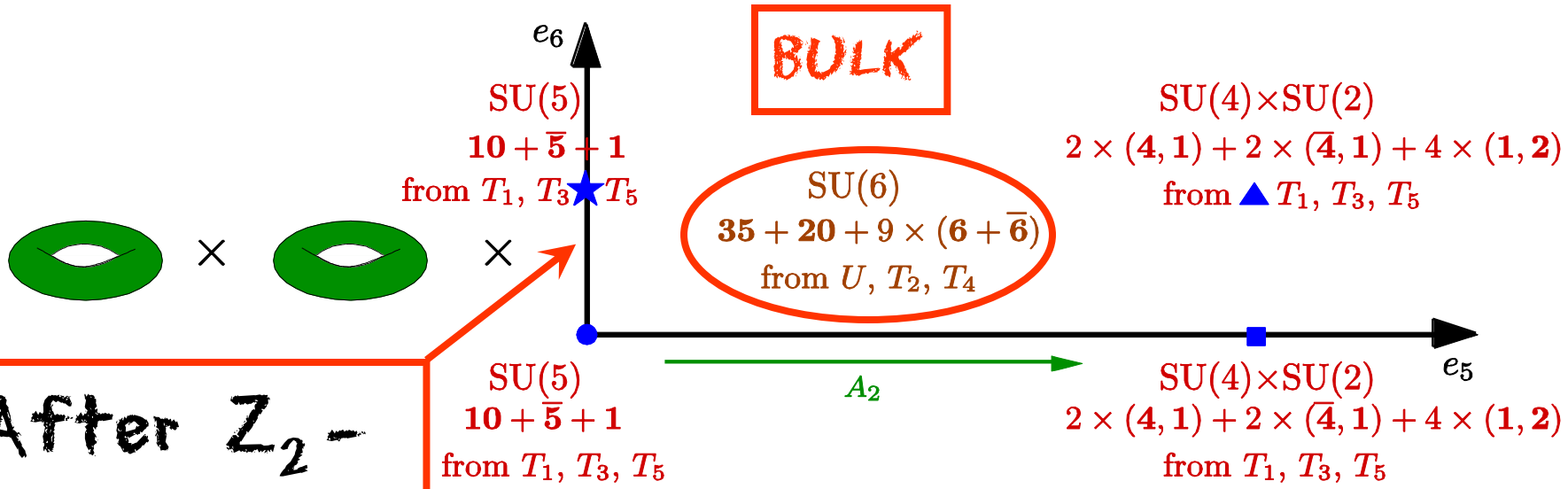


SO(4) root lattice

Local SO(10) GUT

Compactify E(8)xE(8) heterotic string on $(T^2)^3/(Z_3) + A_2$ only $(R_5 \gg l_s)$

→ SU(6) orbifold GUT



After Z_2 - Two light Families on SU(5) brane

$Z'_2 = Z_2 + A_2$

SU(4)xSU(2) brane

"Benchmark" model I - Spectrum

#	irrep	label	#	irrep	label
3	$(\mathbf{3},\mathbf{2};\mathbf{1},\mathbf{1})_{(1/3,1/3)}$	q_i	3	$(\overline{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1})_{(-4/3,-1/3)}$	$\bar{u}_i$
3	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1})_{(2,1)}$	$\bar{e}_i$	8	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1})_{(0,*)}$	m_i
4	$(\overline{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1})_{(2/3,-1/3)}$	$\bar{d}_i$	1	$(\mathbf{3},\mathbf{1};\mathbf{1},\mathbf{1})_{(-2/3,1/3)}$	d_i
4	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1})_{(-1,-1)}$	ℓ_i	1	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1})_{(1,1)}$	$\bar{\ell}_i$
1	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1})_{(-1,0)}$	ϕ_i	1	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1})_{(1,0)}$	$\bar{\phi}_i$
6	$(\overline{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1})_{(2/3,2/3)}$	δ_i	6	$(\mathbf{3},\mathbf{1};\mathbf{1},\mathbf{1})_{(-2/3,-2/3)}$	δ_i
14	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1})_{(1,*)}$	s_i^+	14	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1})_{(-1,*)}$	s_i^-
16	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1})_{(0,1)}$	$\bar{n}_i$	13	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1})_{(0,-1)}$	n_i
5	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{2})_{(0,1)}$	$\bar{\eta}_i$	5	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{2})_{(0,-1)}$	η_i
10	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{2})_{(0,0)}$	h_i	2	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{2})_{(0,0)}$	y_i
6	$(\mathbf{1},\mathbf{1};\mathbf{4},\mathbf{1})_{(0,*)}$	f_i	6	$(\mathbf{1},\mathbf{1};\overline{\mathbf{4}},\mathbf{1})_{(0,*)}$	$\bar{f}_i$
2	$(\mathbf{1},\mathbf{1};\mathbf{4},\mathbf{1})_{(-1,-1)}$	f_i^-	2	$(\mathbf{1},\mathbf{1};\overline{\mathbf{4}},\mathbf{1})_{(1,1)}$	$\bar{f}_i^+$
4	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1})_{(0,\pm 2)}$	χ_i	32	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1})_{(0,0)}$	s_i^0
2	$(\overline{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1})_{(-1/3,2/3)}$	$\bar{v}_i$	2	$(\mathbf{3},\mathbf{1};\mathbf{1},\mathbf{1})_{(1/3,-2/3)}$	v_i

Table 1: Spectrum. The quantum numbers under $SU(3)\times SU(2)\times[SU(4)\times SU(2)']$ are shown, hypercharge and B-L charge appear as subscript.

S

Conclusions

Evolution of SUSY GUT Model Building

Bottom up

- 4D SUSY GUT + family symmetry
  test predictions via global analysis
- Lift to 5D (or 6D) orbifold GUT

Top down

- Derive from heterotic string,
  M or F theory

includes Gravity !!

Problems with String constructions

μ problem - Why is $\mu \ll M_G$???

Dimension 5 proton decay is unsuppressed !!!

Unique $\mathbb{Z}_4^R$ symmetry

Lee, Raby, Ratz, Ross, Schieren,
Schmidt-Hoberg & Vaudrevange

arXiv:1009.0905 (hep-ph)

arXiv:1102.3595 (hep-ph)

Kappl, Peterson, Raby, Ratz, Schieren
& Vaudrevange

arXiv:1012.4574 (hep-th)

Unique discrete R symmetry consistent with SO(10)

$$\mathbb{Z}_4^R$$

SU(5)

$q_{\mathbf{10}}$	$q_{\bar{\mathbf{5}}}$	q_{H_u}	q_{H_d}
1	1	0	0

SO(10)

$$q_{16} = q_{10} = q_{\bar{5}} = q_1 = 1$$

$$q_{10} = q_{H_u} = q_{H_d} = 0$$

$\mathbb{Z}_4^R$

$\mathcal{W}$	2	
$Q\,\bar{U}\,H_u, \ldots$	2	*Good*
$(L\,H_u)^2$	2	
$\bar{U}\,\bar{D}\,\bar{D}$	3	
$Q\,L\,\bar{D}$	3	*R parity viol.*
$L\,L\,\bar{E}$	3	
$H_u\,L$	1	
$H_u\,H_d$	0	*μ term*
$Q\,Q\,Q\,L$	0	*proton*
$\bar{U}\,\bar{U}\,\bar{D}\,\bar{E}$	0	*decay*

$$\mathcal{W}_p = Y_e^{ij} H_d L_i \bar{E}_j + Y_d^{ij} H_d Q_i \bar{D}_j + Y_u^{ij} H_u Q_i \bar{U}_j$$
$$+ \kappa_{ij}^{(0)} H_u L_i H_u L_j$$

$$\mathcal{W} = \mathcal{W}_p + \Delta\mathcal{W}_{non-perturbative}$$

Non-perturbative effects

$$
\begin{aligned}
\zeta \;:\; \text{matter superfield} &\;\to\; \mathrm{i}\cdot\text{matter superfield}\,,\\
\text{Higgs superfield} &\;\to\; \text{Higgs superfield}\,,\\
\theta &\;\to\; \mathrm{i}\cdot\theta\,,\\
\mathscr{W} &\;\to\; -\mathscr{W}\,.
\end{aligned}
$$

$$S \to S + \frac{i}{2}\Delta_{GS} \qquad \Delta\mathcal{W}_{np} \propto \langle \mathcal{W} \rangle_0 (\cdots)$$

$$
\begin{aligned}
\Delta\mathscr{W}_{\rm np} \;=\; \exp\left(-8\pi^2\,\frac{1+2n}{1+2\nu}\,S\right)\;\Big[&B_0 + \overline{\mu}\,H_u\,H_d + \overline{\kappa}^{(1)}_{ijk\ell}\,Q_i\,Q_j\,Q_k\,L_\ell\\
&+ \overline{\kappa}^{(2)}_{ijk\ell}\,\overline{U}_i\,\overline{U}_j\,\overline{D}_k\,\overline{E}_\ell\Big]
\end{aligned}
$$

$$\langle W \rangle_0 / M_{Pl}^2 \sim m_{3/2}$$

Gravity mediation

$$\Delta W_{np} \propto m_{3/2} M_{Pl}^2 + m_{3/2} H_u H_d$$

$$+ \frac{m_{3/2}}{M_{Pl}^2} \left(Q Q Q L + \bar{U} \bar{U} \bar{D} \bar{E} \right)$$

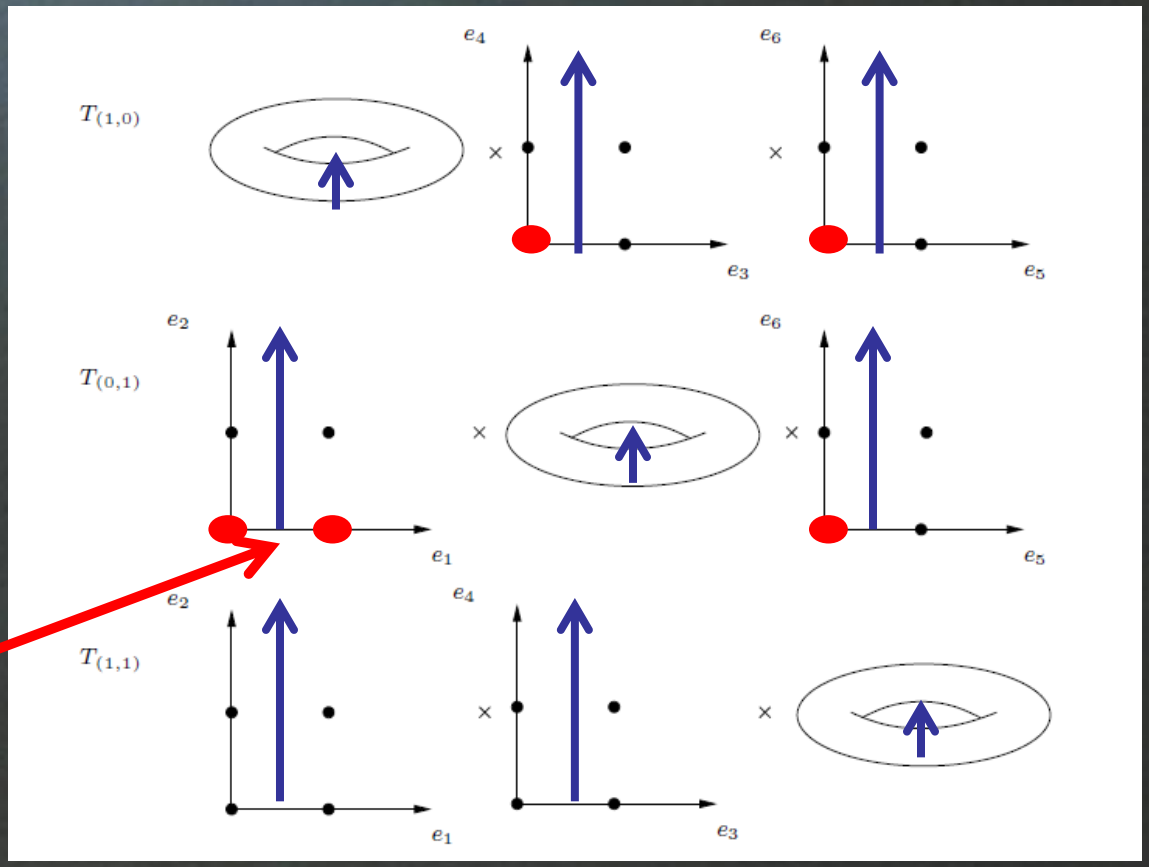
$$\mu \approx m_{3/2}$$

$$\frac{1}{\Lambda} \approx \frac{m_{3/2}}{M_{Pl}^2} \approx 10^{-33}\ \text{GeV}^{-1}$$

E(8)xE(8) heterotic string compactified on $(T^2)^3/(Z_2 \times Z_2)$ orbifold w/ $\mathbb{Z}_4^R$

Kappl, Peterson, Raby, Ratz, Schieren & Vaudrevange

NPB 847, 325 (2011)



Two light Families on SO(10) fixed pts

heterotic orbifolds

- E(8)xE(8) heterotic string compactified on $(T^2)^3 /(Z_2 \times Z_2)$ orbifold
- exact MSSM spectrum
- F = D = 0 verified
- $\mathbb{Z}_4^R$ comes partially from the Lorentz symmetry of the internal dimensions
- $\mu = 0$ due to $\mathbb{Z}_4^R$
- gauge – top Yukawa unification
- non-trivial Yukawa matrices
- local SO(10) gauge symmetry
- D(4) family symmetry

Conclusions

Top down analysis, i.e. Embed SUSY GUT in String Theory

a) Need to have $\mu << M_G$

b) Need to suppress dimension 5 operators

$\Rightarrow$ $\mathbb{Z}_4^R$ symmetry ξ

Proton decay via Dim 6 ops. dominates

$$\Rightarrow \quad p \to e^+ \pi^0, \quad n \to e^+ \pi^-$$

Proton decay rate typically enhanced !!!